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19. ABSTRACT (Continue on reverse if necessary and identify by block number)

The nonlinear, stalled, aeroelastic behavior of rectangular, graphite/epoxy, cantilevered plates with varying amounts of bending-torsion stiffness coupling and with NACA 0012 Styrofoam airfoil shapes is investigated for low Reynolds number flow (<200,000). A general Rayleigh-Ritz formulation is used to calculate point load static deflections, and nonlinear static vibration frequencies and mode shapes for varying tip deflections. Nonlinear lift and moment aerodynamics are used in the context of the Rayleigh-Ritz formulation to calculate static airload deflections. The nonlinear, stalled ONERA model using non-constant coefficients - initially developed by Tran & Petot - is reformulated into a harmonic balance form and compared against a time-marching Runge-Kutta scheme. Low angle-of-attack, linear flutter calculations are done by applying Fourier analysis to extract the harmonic balance method and a Newton-Raphson solver to the resulting nonlinear, Rayleigh-Ritz aeroelastic formulation.

Test wings were constructed and subjected to static, vibration, and wind tunnel tests. Static

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TITLE: NONLINEAR AEROELASTICITY OF COMPOSITE STRUCTURES

(AFOSR Contract No. F49620-86-C-0066)

Principal Investigator: John Dugundji

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OVERVIEW:

There are few analytic studies of nonlinear stall flutter, most studies being experimental, and recently, of the computational fluid dynamic type. The present investigation develops an analytic method to include the nonlinear aerodynamic and structural effects into a full 3-dimensional, aeroelastic problem, using the mathematical tools of Fourier analysis, harmonic balance, and the Newton-Raphson method as a numerical solver. The nonlinear aerodynamics are introduced using the ONERA stall flutter model[1] while the nonlinear structures are introduced by moderate deflection cantilever beam theories such as Hodges & Dowell[2] which is used in helicopter theory and involves coupling of traditional bending and torsion modes with fore-and-aft modes. It is hoped that this new nonlinear analysis, and the attendant flutter experiments on various aeroelastically tailored composite wings, will shed important light on the phenomenon of high angle-of-attack stall flutter, its severity, and how it evolves out of small amplitude, linear flutter at low angles-of-attack.

SUMMARY OF ACCOMPLISHMENTS:

A combined experimental and analytic program was undertaken to investigate the nonlinear stall flutter and divergence behavior of aeroelastically tailored composite wings. Experimentally, a set of zero sweep cantilever wing models, of length 30 cm, were constructed from flat composite plates covered with styrofoam fairings to give NACA 0012 contours. The wings had varying amounts of bending-torsion coupling ranging from positive to negative values. Tests were conducted in the wind tunnel at varying root angles as shown in Fig.1. These tests revealed linear flutter and divergence as well as nonlinear torsion stall flutter and bending stall flutter. Flutter velocity boundaries, frequencies, limit cycles, and static deflection were observed at different root angles of attack. Analytically, a new nonlinear flutter analysis technique was developed based on the ONERA aerodynamic stall model, together with simple frequency and harmonic balance techniques to obtain the resulting nonlinear stall limit cycles that can arise from aeroelastic instabilities. Both torsional stall and bending stall flutter limit cycles were successfully predicted by this technique and matched the observed experimental behavior. Figure 2 shows the flutter boundary versus root angle of attack for a typical wing with no bending - twist coupling, while Fig.3 shows the boundary when positive coupling is present. Accompanying static positions and limit cycle amplitudes for Fig.2 are shown in Fig.4, indicating a torsional stall flutter situation, while the corresponding quantities for Fig.3 indicated a bending stall flutter situation (also note the much lower flutter frequency in Fig.3 corresponding to the bending mode rather than the torsion mode). A detailed report on this work is given by Dunn[3], while a paper summarizing some of these results was presented at the 31st AIAA SDM Conference last year[4].

An additional set of composite wings, twice the size of the previous wings was also constructed and tested. This yielded improved, high quality experimental data to compare with the analysis, and to observe the transitions from classical linear low angle of attack flutter to stall flutter at high angles of attack. Supplementing this new data, an expanded nonlinear analytical effort was pursued using more modes and including fore-and-aft motion of the wings as well as the usual bending and torsion motions. These fore-and-aft motions couple in nonlinearly into the analysis, and were also observed during the tests.

To summarize, an analytical method was developed to incorporate nonlinear structural and aerodynamic stall effects into a full, 3D aeroelastic flutter analysis. High quality stall flutter data was obtained to check the new nonlinear analysis. Transitions from linear, coupled-mode, bending-torsion flutter to single-mode, torsional stall flutter was observed experimentally and predicted analytically. Also transition from linear divergence to bending stall flutter was observed experimentally and predicted analytically. These experimental and nonlinear analytic results should be of interest in understanding stall flutter at high angles of attack.

REFERENCES:

1. Tran, C.T., and Petot, D., "Semi-Empirical Model for the Dynamic Stall of Airfoils in View of Application to the Calculation of Responses of a Helicopter in Forward Flight", Vertica, Vol. 5, No. 1, 1981, pp.35-53.

2. Hodges, D.H., and Dowell, E.H., "Nonlinear Equations of Motion for the Elastic Bending and Torsion of Twisted Nonuniform Rotor Blades", NASA TN D-7818, December 1974.

3. Dunn, P.E., "Stall Flutter of Graphite/Epoxy Wings with Bending-Torsion Coupling", M.S. Thesis, Dept. of Aeronautics & Astronautics, M.I.T., May, 1989. (Also TELAC Rept. 89-5, M.I.T., May 1989.)

4. Dunn, P.E., and Dugundji, J., "Nonlinear Stall Flutter and Divergence Analysis of Cantilevered Graphite/Epoxy Wings", 31st AIAA/ASME/ASCE/AAHHS/ASC Structures, Structural Dynamics and Materials Conference, Long Beach, CA April 2-4, 1990, AIAA Paper 90-0983. (Also, to be published in the AIAA Journal.)

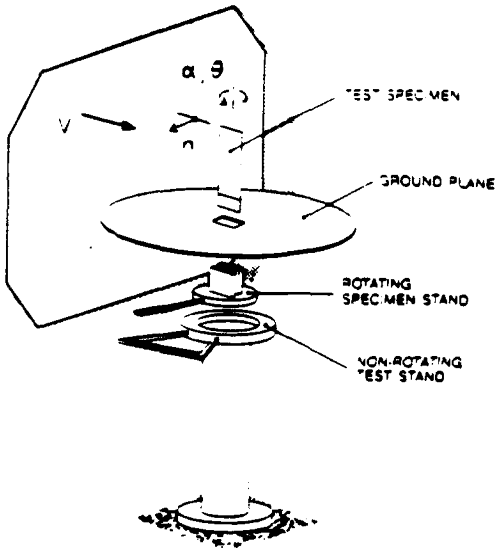

Fig. 1 Wind Tunnel Setup

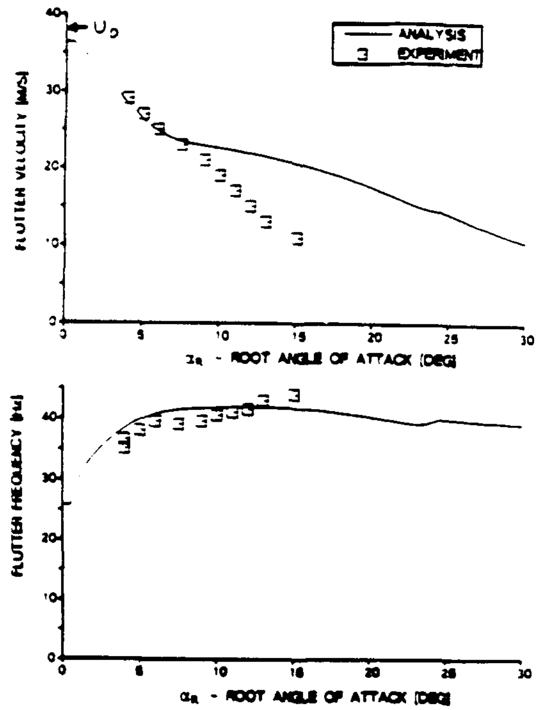

Fig. 2 $[0_2/90]_S$ Flutter Boundary and Frequency

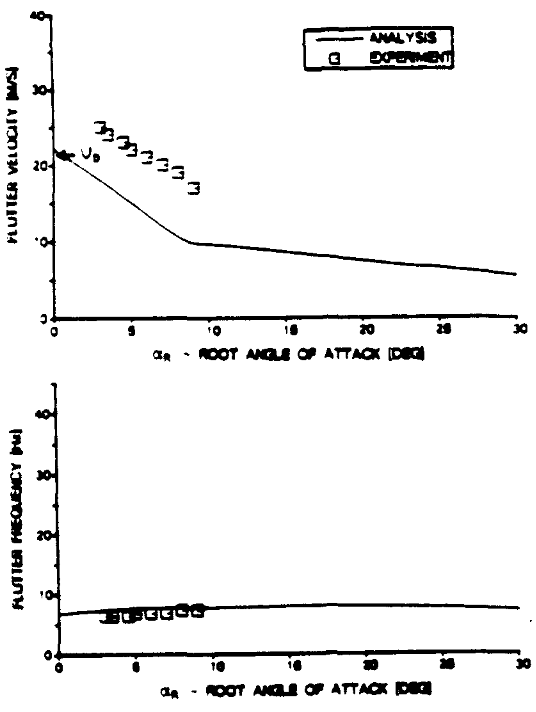

Fig. 3 $[-15_2/0]_S$ Flutter Boundary and Frequency

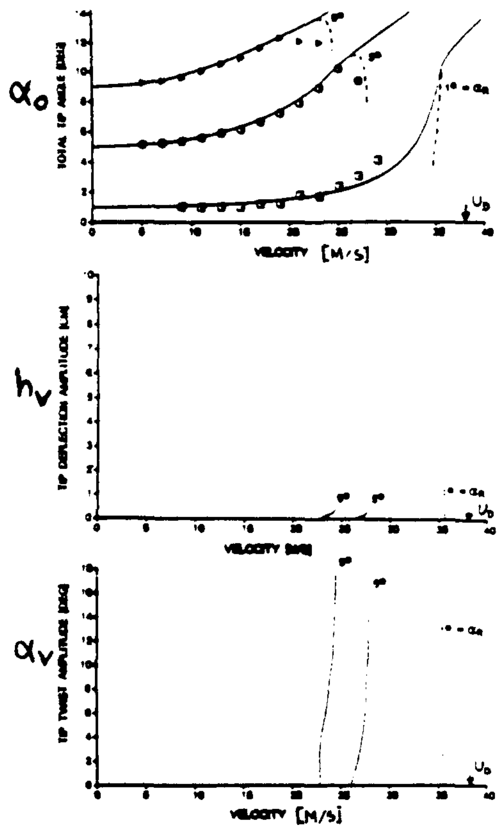

Fig. 4 $[0_2/90]_S$ Deflections and Angle Oscillation Amplitudes

FOREWORD

The following pages represent a more detailed summary of the work performed on this contract. They are from a technical presentation given on October 10, 1991 at the Air Force Office of Scientific Research Contractor's Meeting on Structural Dynamics at Datyon, Ohio.

NONLINEAR STALL FLUTTER and DIVERGENCE ANALYSIS of CANTILEVERED GRAPHITE/EPOXY WINGS

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OBJECTIVES

- Investigate nonlinear structures and nonlinear aerodynamics in large-amplitude, high angle-of-attack, stall flutter of aeroelastically tailored wings

- Develop method to incorporate nonlinear effects (aerodynamic and structural) into a flutter analysis

- Develop in context of simple, modal flutter analysis to keep computational costs low

- Concurrently develop experimental base of small and large amplitude flutter data for variety of composite laminate wings

ANALYSIS - RAYLEIGH-RITZ MODEL

$$w(x,y,t) = \sum_i \gamma_i(x,y)\, q_i(t) = \sum_i \phi_i(x)\, \psi_i(y)\, q_i(t)$$

$$K_{ij} = \iint_A \{ D_{11}\gamma_{i,xx}\gamma_{j,xx} + D_{22}\gamma_{i,yy}\gamma_{j,yy} + 4D_{66}\gamma_{i,xy}\gamma_{j,xy} + D_{12}[\gamma_{i,xx}\gamma_{j,yy} + \gamma_{i,yy}\gamma_{j,xx}] + 2D_{16}[\gamma_{i,xx}\gamma_{j,xy} + \gamma_{i,xy}\gamma_{j,xx}] + 2D_{26}[\gamma_{i,yy}\gamma_{j,xy} + \gamma_{i,xy}\gamma_{j,yy}] \}\, dA$$

$$M_{ij} = \iint_A m\gamma_i\gamma_j \, dA$$

$$Q_i = \iint_A f(x,y)\, \gamma_i(x,y)\, dA = \iint_A f(x,y)\, \phi_i(x)\, \psi_i(y)\, dA$$

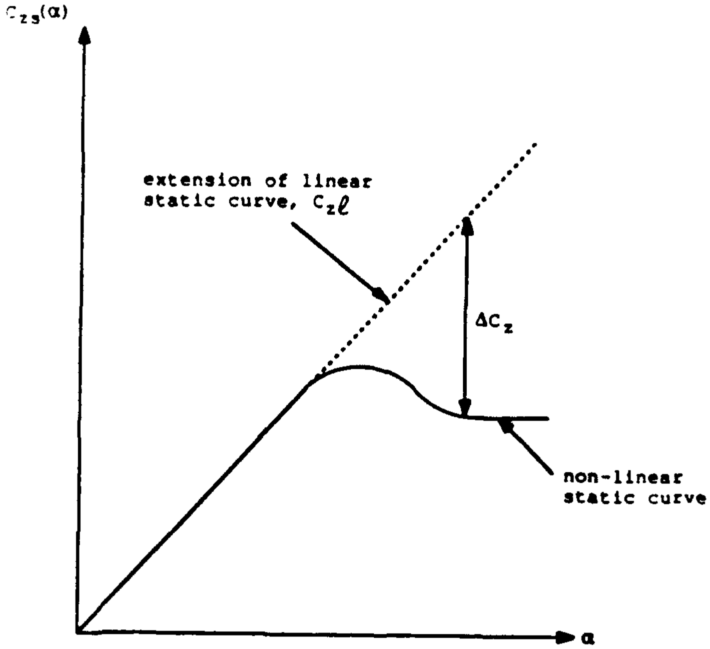
$$[M]\{\ddot{q}\} + [K]\{q\} = \{Q\}$$

- Mass and stiffness of styrofoam calculated and added to overall matrices

- Empirical cubic stiffening added to torsional mode

$$K_{22} = K_{22}^{L} + K_{22}^{C} q_2^2$$

ANALYSIS – AERODYNAMICS



$$C_z = C_{z1} + C_{z2}$$

$$C_{z1} = s_z\overset{*}{\alpha} + k_{vz}\overset{**}{\theta} + C_{z\gamma}$$

$$\overset{*}{C}_{z\gamma} + \lambda_z C_{z\gamma} = \lambda_z[a_{oz}\alpha + \sigma_z\overset{*}{\theta}] + \alpha_z[a_{oz}\overset{*}{\alpha} + \sigma_z\overset{**}{\theta}]$$

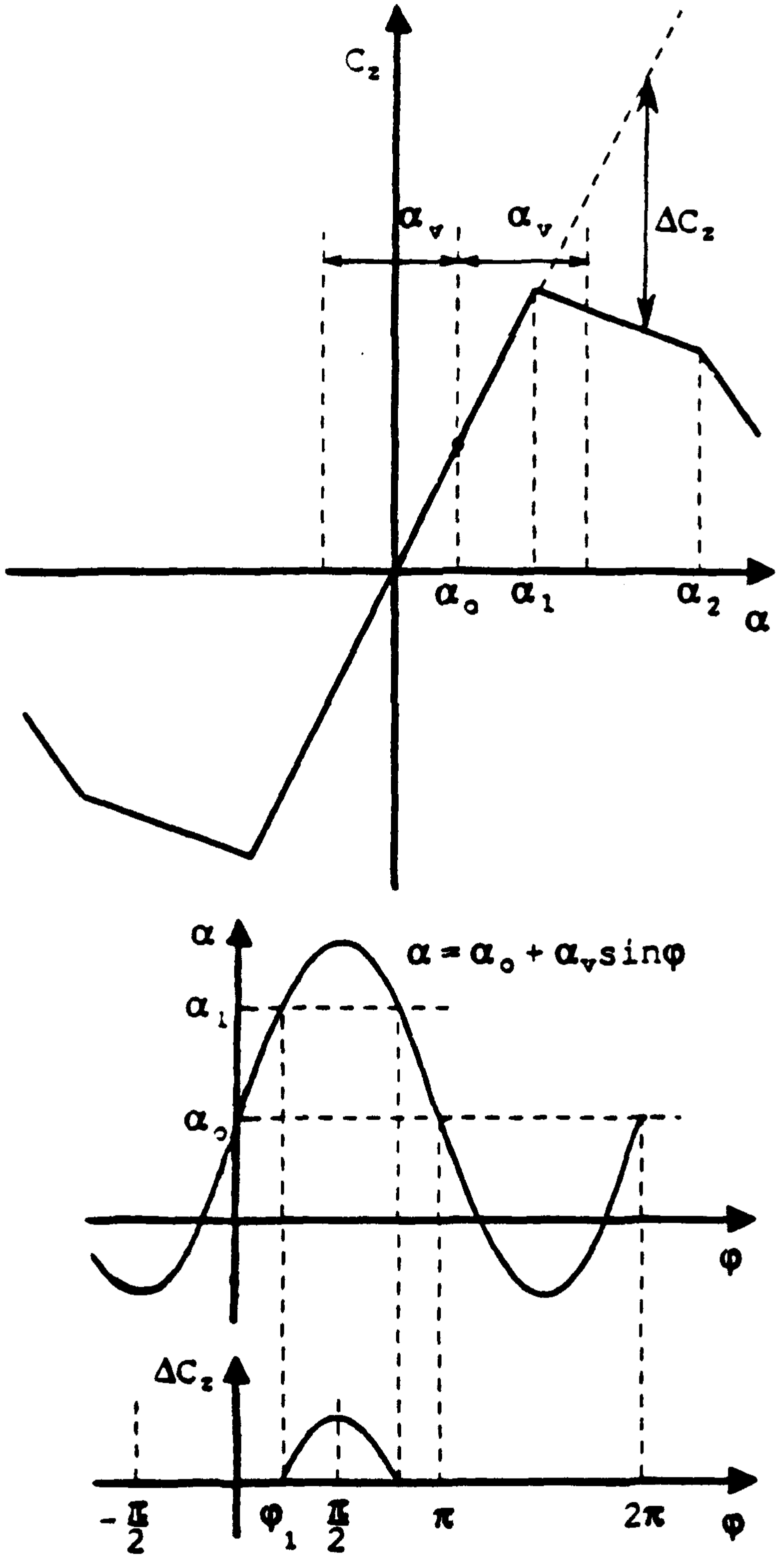
$$\overset{**}{C}_{z2} + 2dw\overset{*}{C}_{z2} + w^2(1+d^2)C_{z2} =$$
$$= -w^2(1+d^2)\left[\Delta C_z\Big|_\alpha + e\frac{\partial \Delta C_z}{\partial \tau}\Big|_\alpha\right]$$

where,

$$\alpha = \theta - \overset{*}{h} \quad ; \qquad (\overset{*}{\ }) \equiv \frac{\partial(\ )}{\partial \tau} \quad ; \qquad \tau \equiv \frac{Ut}{b}$$

- Aerodynamic model from ONERA
- Coefficients determined semi-empirically
- 2D aerodynamics at each spanwise location, corrected for finite span (3D) effects, integrated to give modal forces

ANALYSIS – FOURIER ANALYSIS



ANALYSIS – FOURIER ANALYSIS

- Assume polynomial form to aerodynamic curve,

$$\Delta C_z(\alpha) = \sum_{j=0}^{J_i} a_{ij}(\alpha - \alpha_i)^j \quad ; \quad \alpha_i \le \alpha \le \alpha_{i+1}$$

- Sinusoidal input for effective angle of attack,

$$\alpha(\tau) = \alpha_o + \alpha_v \sin\varphi = \alpha_o + \alpha_s \sin(k\tau) + \alpha_c \cos(k\tau)$$

$$\varphi = k\tau + \xi \quad ; \quad \alpha_v = \sqrt{\alpha_s^2 + \alpha_c^2} \quad ; \quad \xi = \sin^{-1}\frac{\alpha_c}{\alpha_v}$$

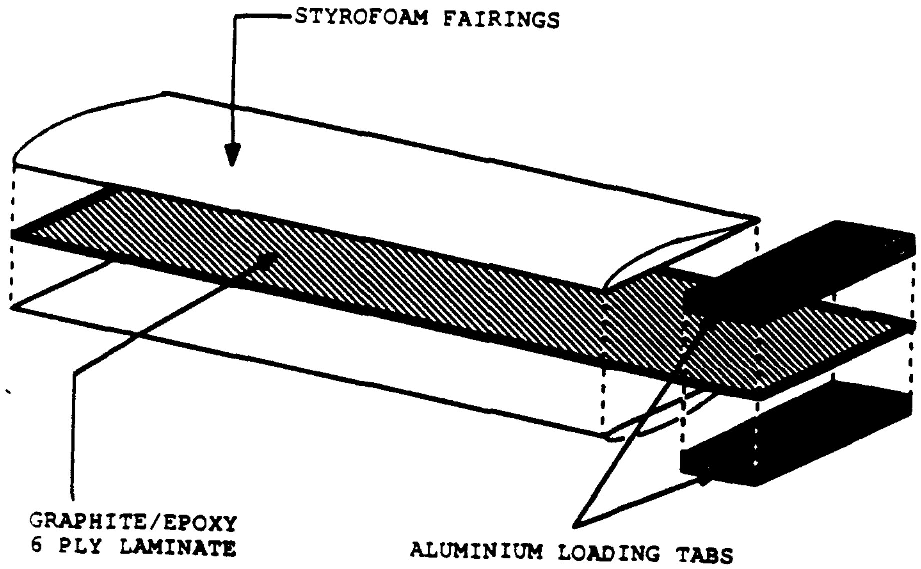
- Fourier analysis for harmonic components of ΔC_Z

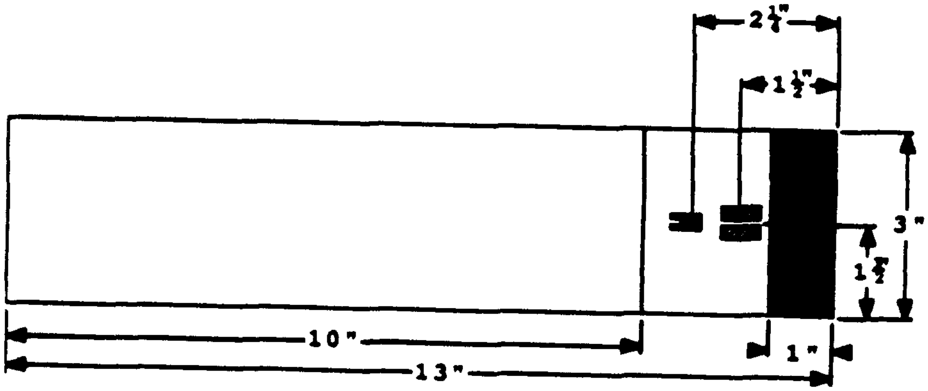
$$\Delta C_{zo} = \frac{1}{2\pi}\int_{-\pi}^{+\pi} \Delta C_z(\tau)\, d\varphi = \frac{1}{\pi}\int_{-\frac{\pi}{2}}^{+\frac{\pi}{2}} \Delta C_z(\tau)\, d\varphi$$

$$\Delta C_{zv} = \frac{2}{\pi}\int_{-\frac{\pi}{2}}^{+\frac{\pi}{2}} \Delta C_z(\tau) \sin\varphi \, d\varphi$$

EXPERIMENT

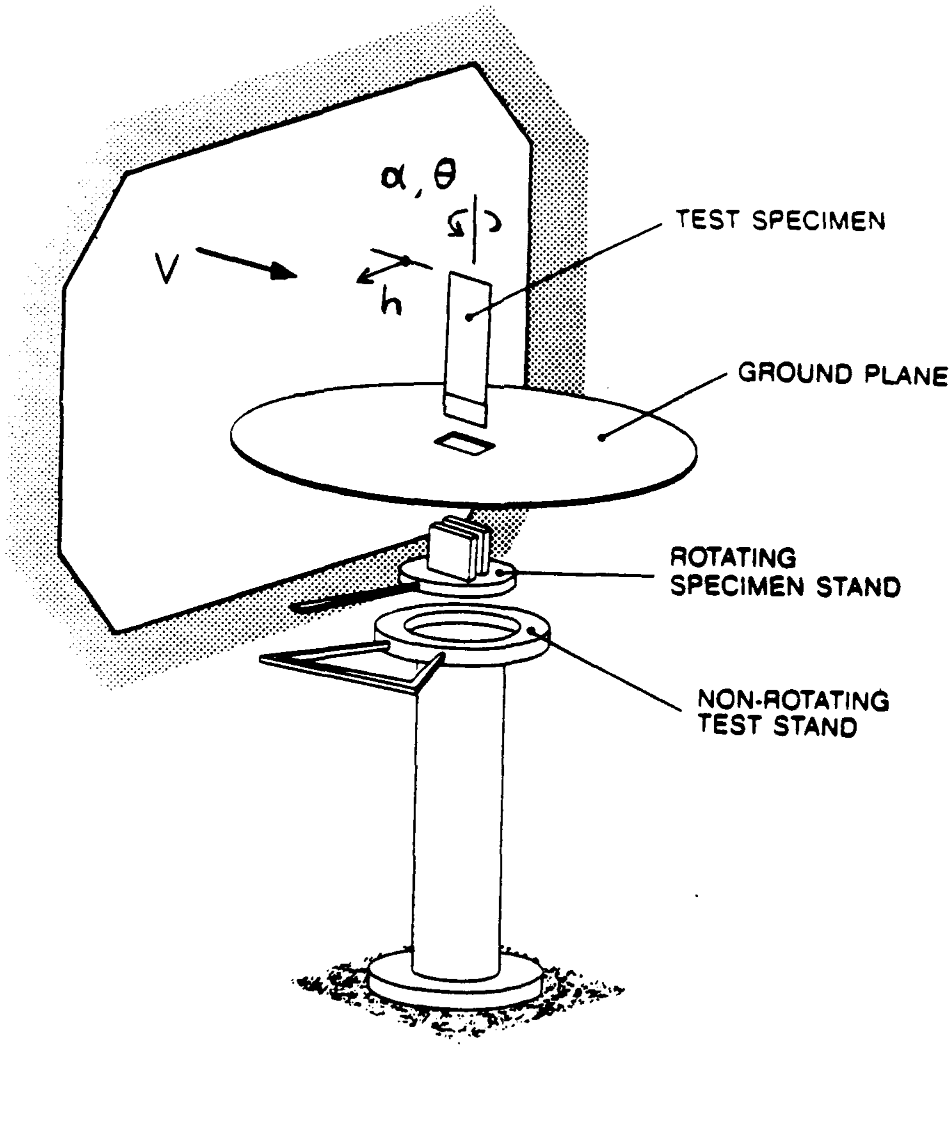
- Hercules AS4/3501-6 graphite/epoxy test specimens
- $[0_2/90]_S$, $[+15_2/0]_S$, $[-15_2/0]_S$ layups



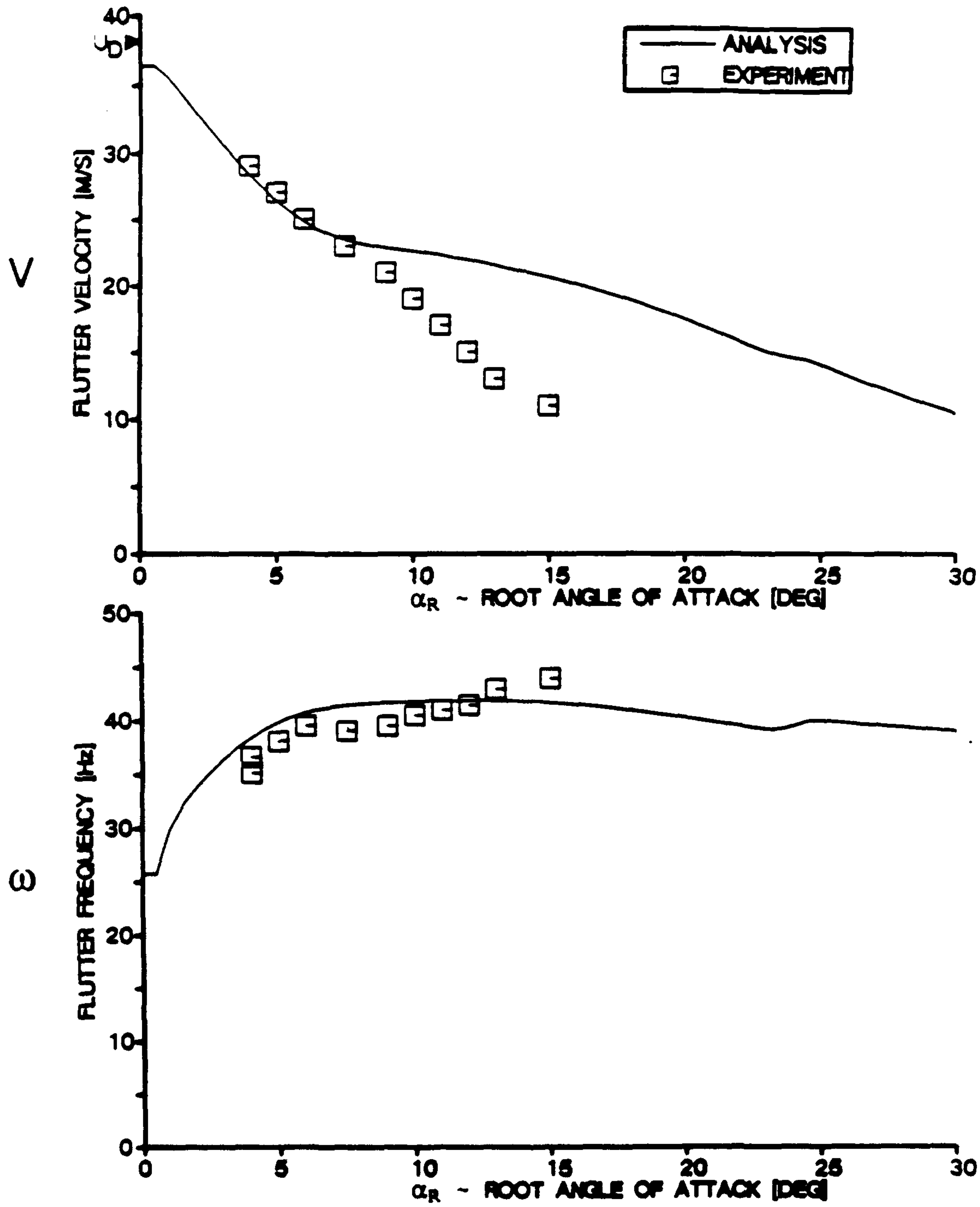


EXPERIMENT

- Wind tunnel tests in 5' x 7.5' free jet test section
- Data from strain gauges and visual data on video

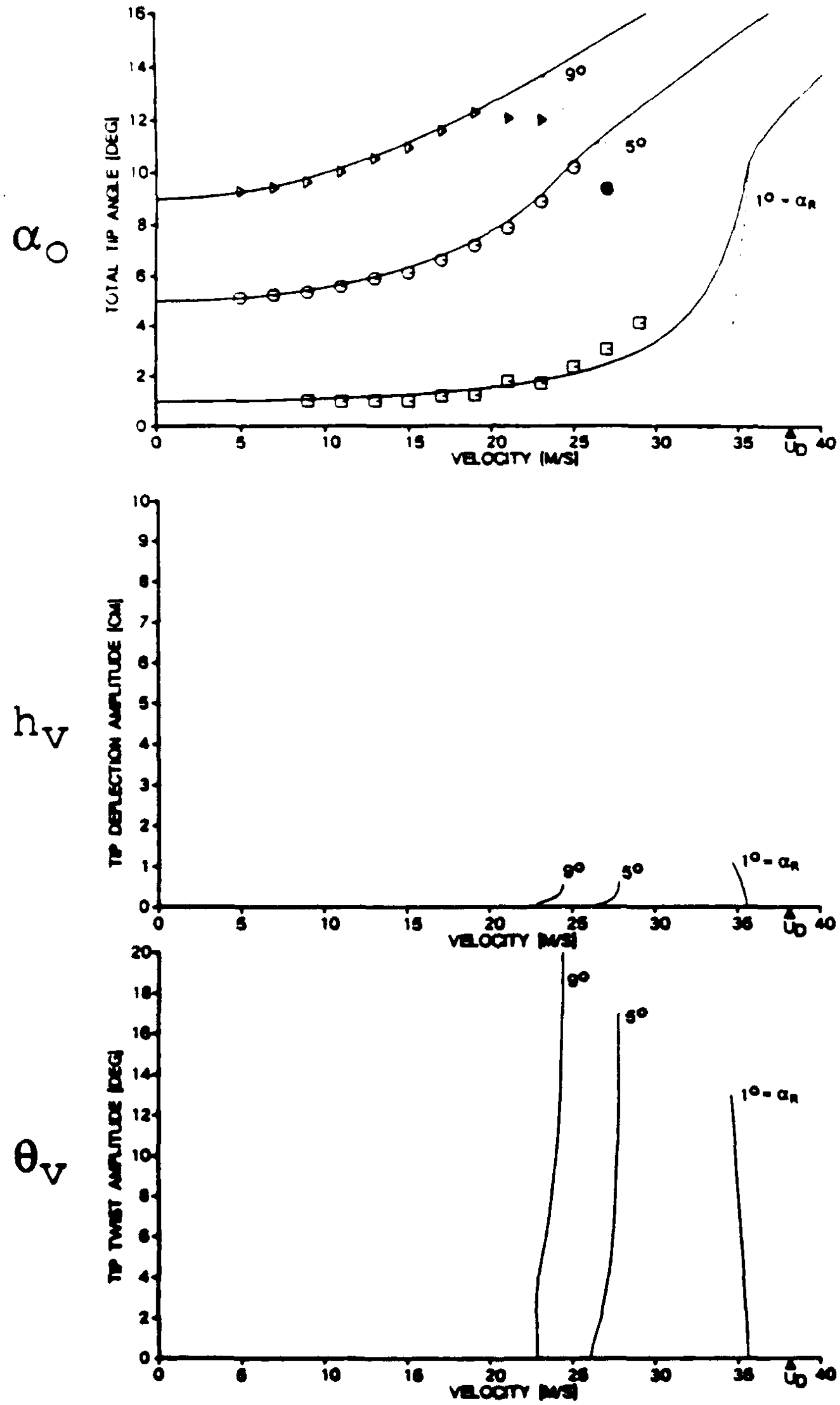


RESULTS - $[0_2/90]_s$



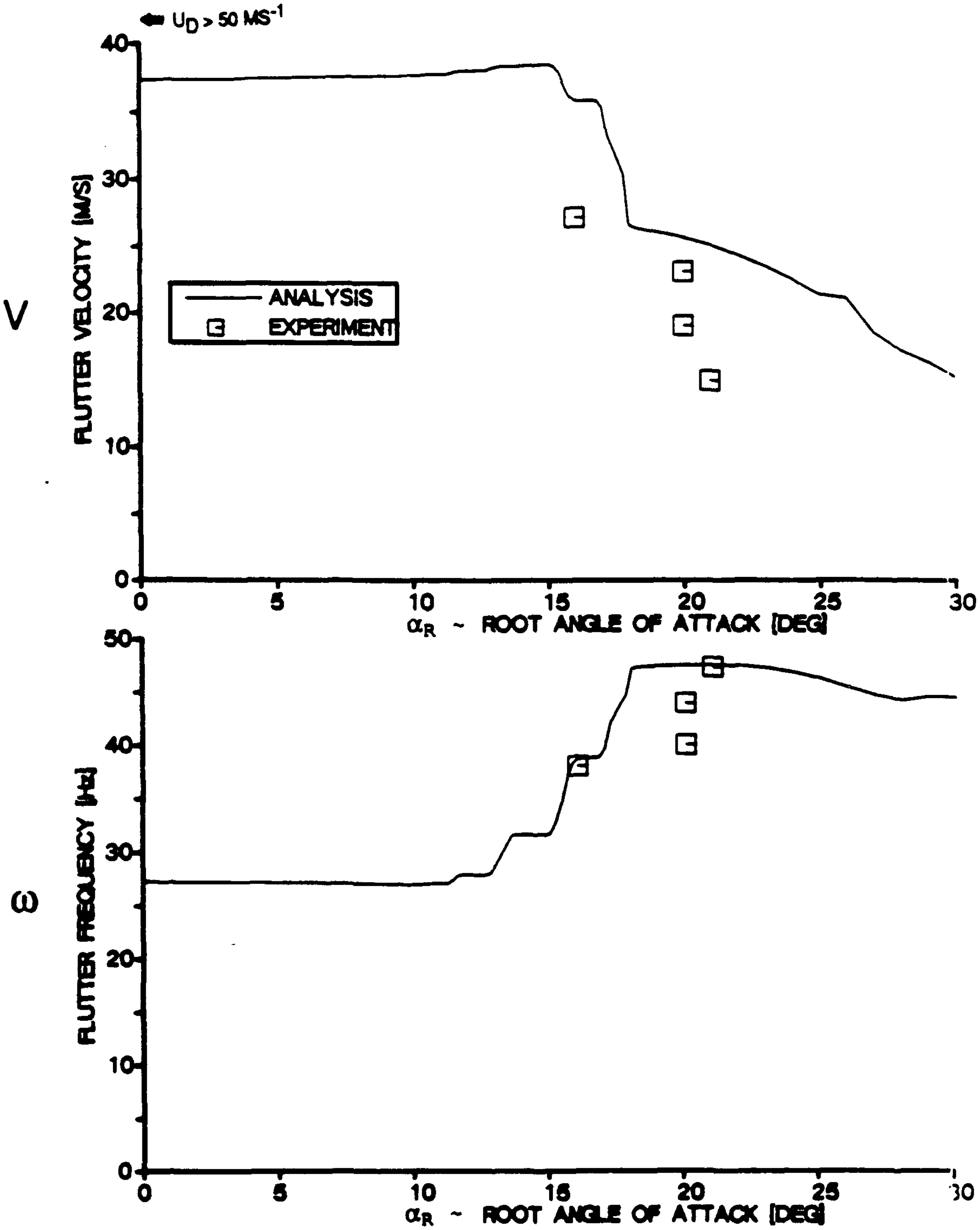
Flutter boundary and frequency variation

RESULTS - $[0_2/90]_s$



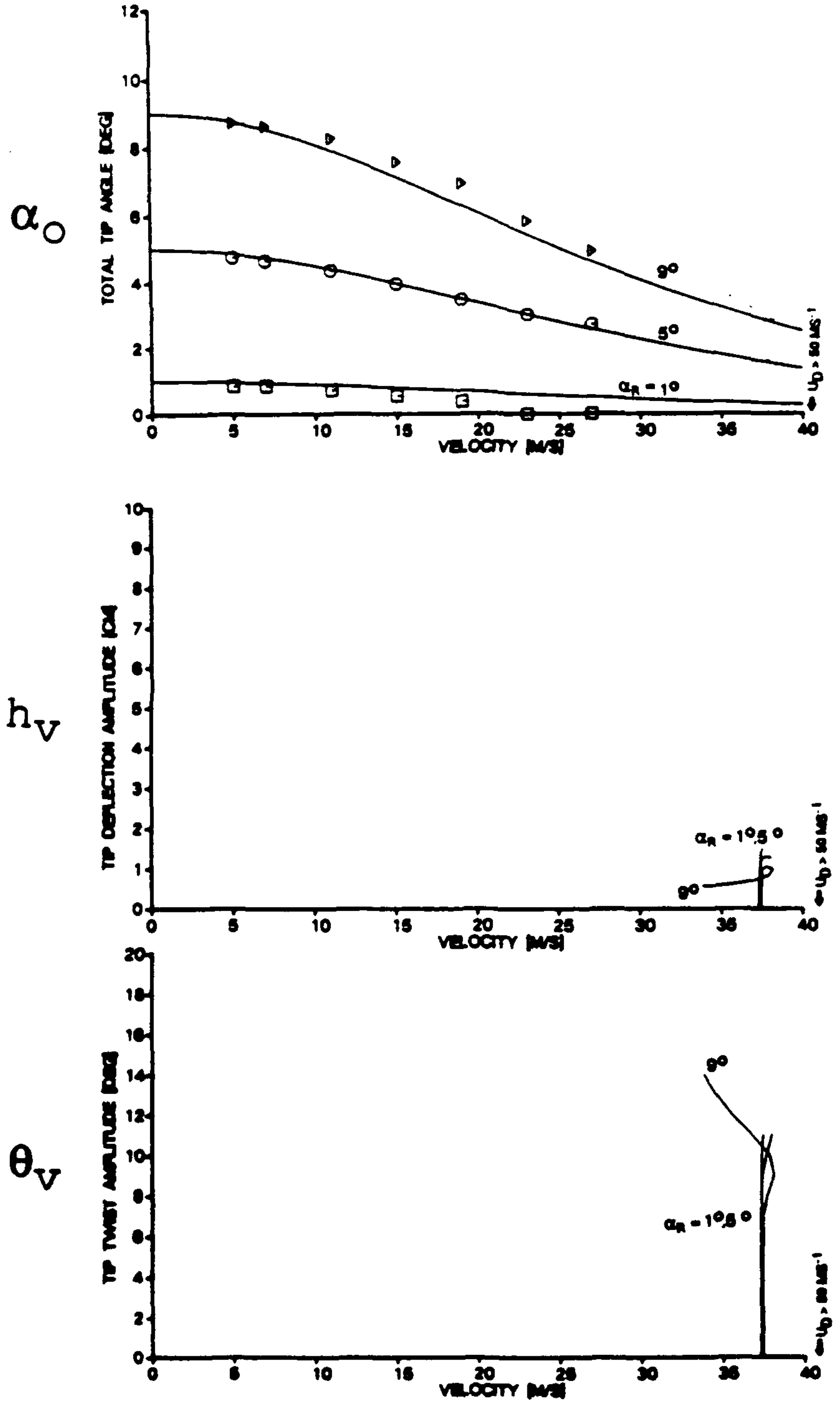
Tip angle, and deflection & angle oscillation amplitudes
(no cubic stiffening)

RESULTS - $[+15_2/0]_s$



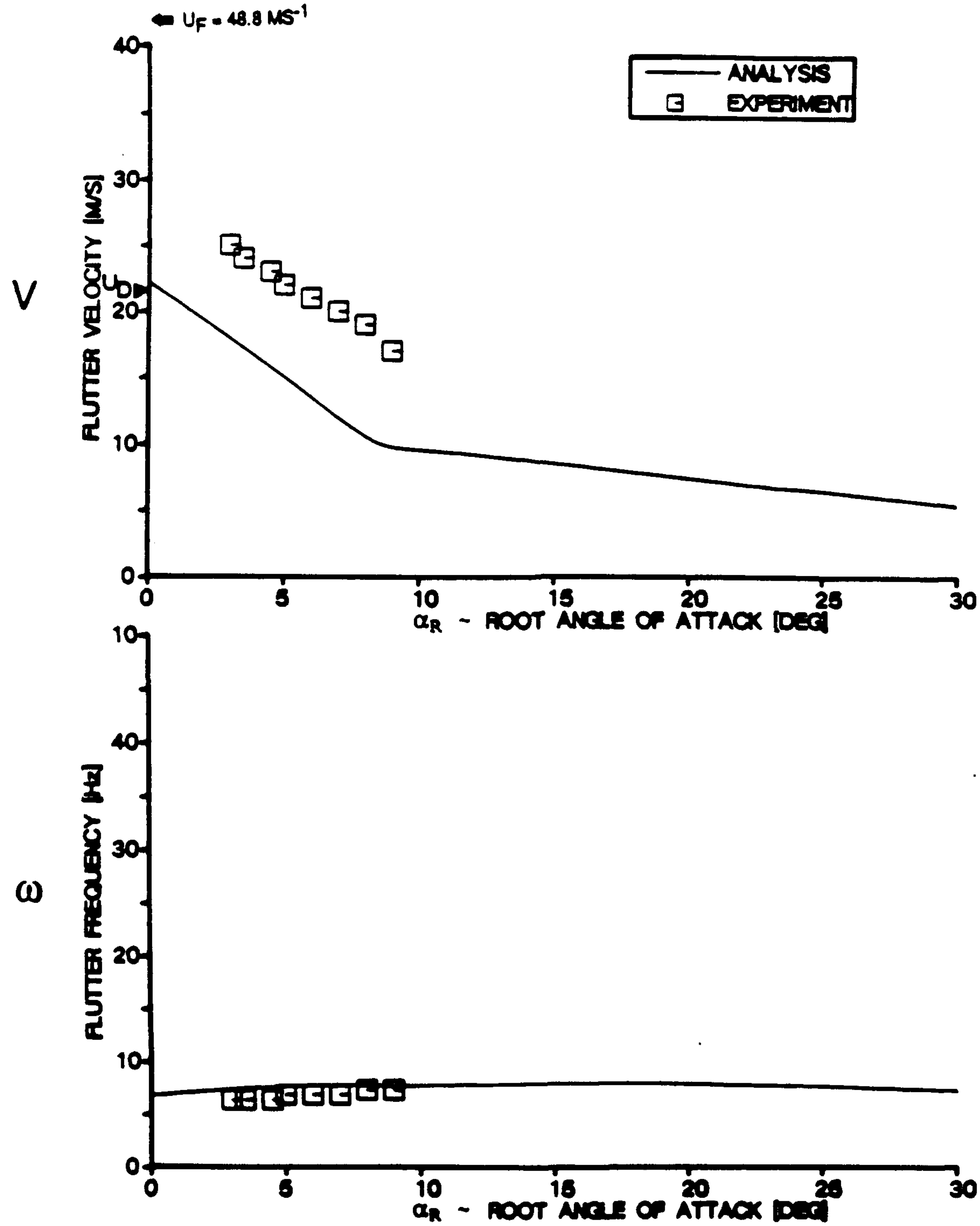
Flutter boundary and frequency variation

RESULTS – $[+15_2/0]_s$



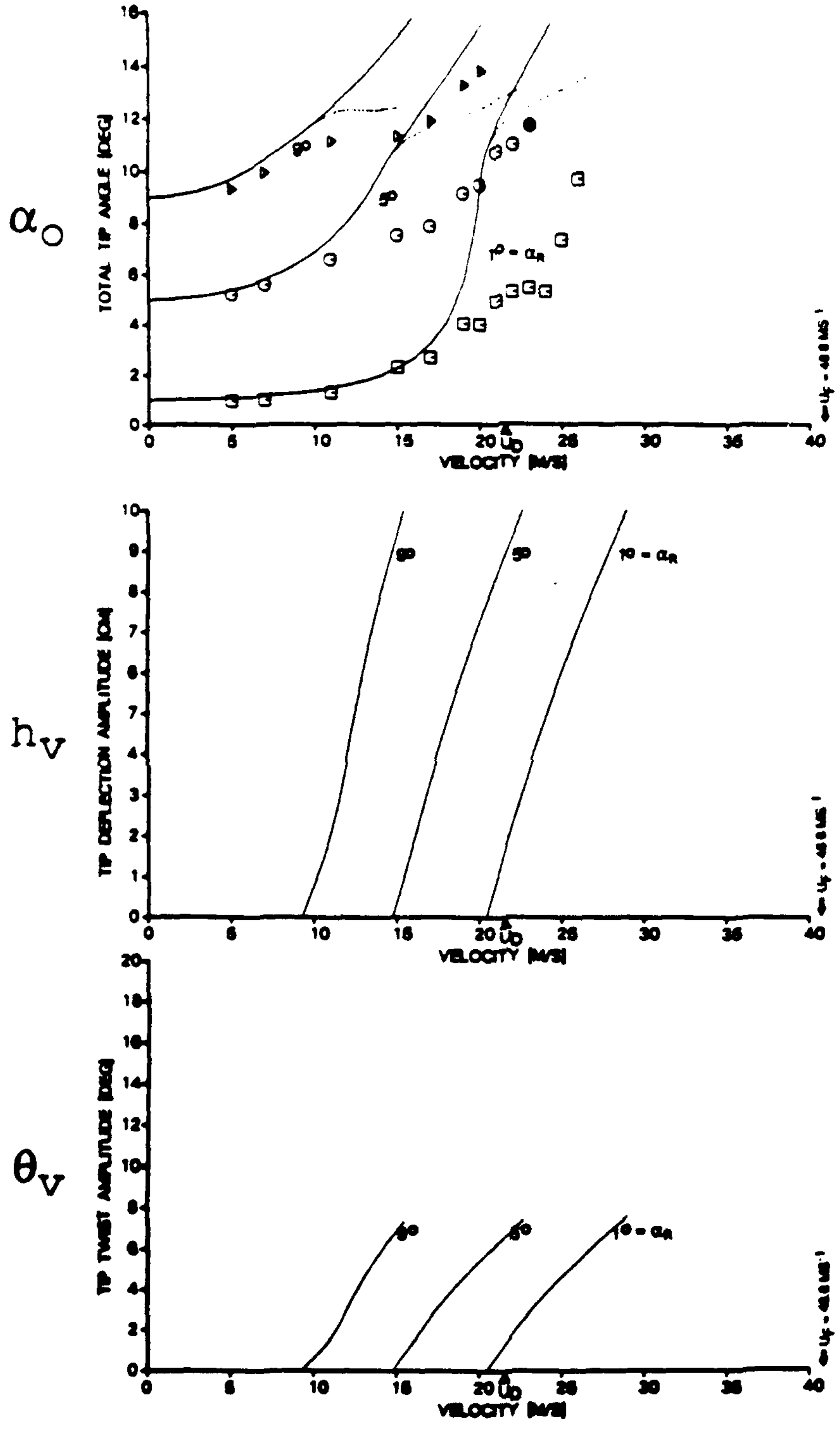
Tip angle, and deflection & angle oscillation amplitudes

RESULTS – $[-15_2/0]_s$



Flutter boundary and frequency variation

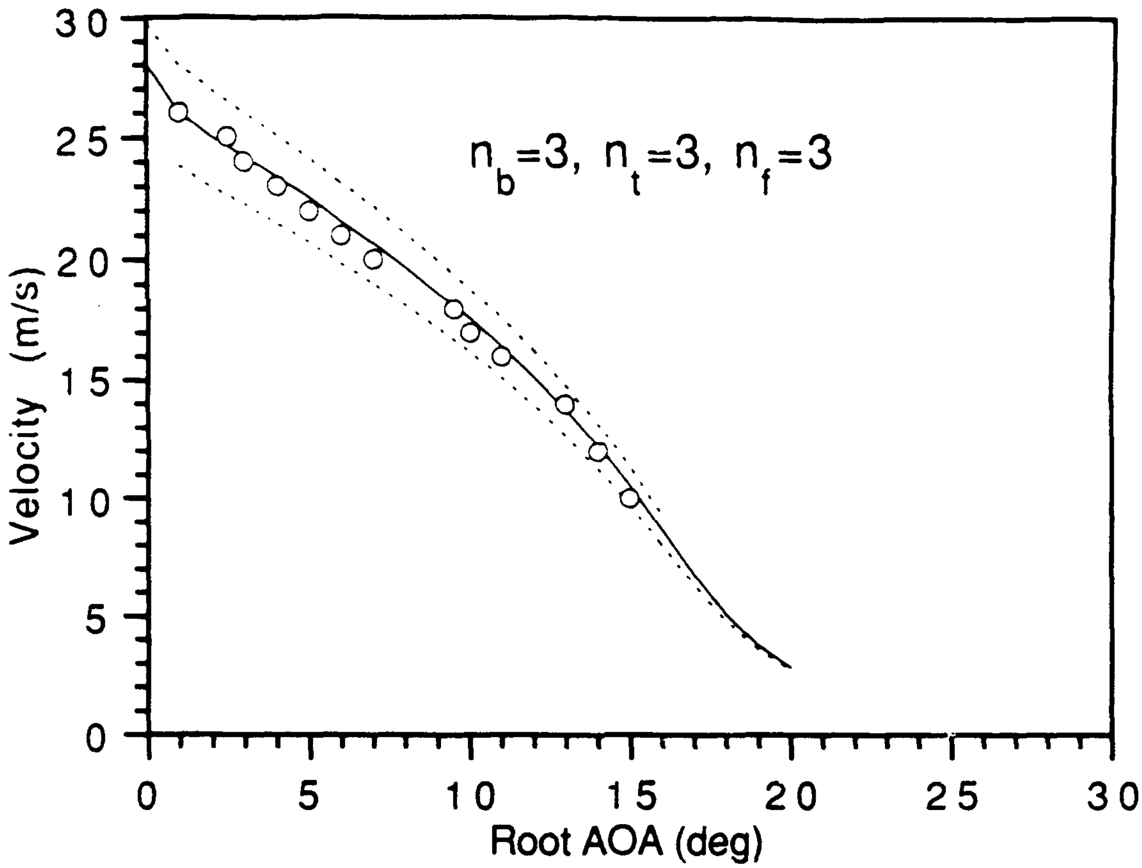
RESULTS – $[-15_2/0]_s$



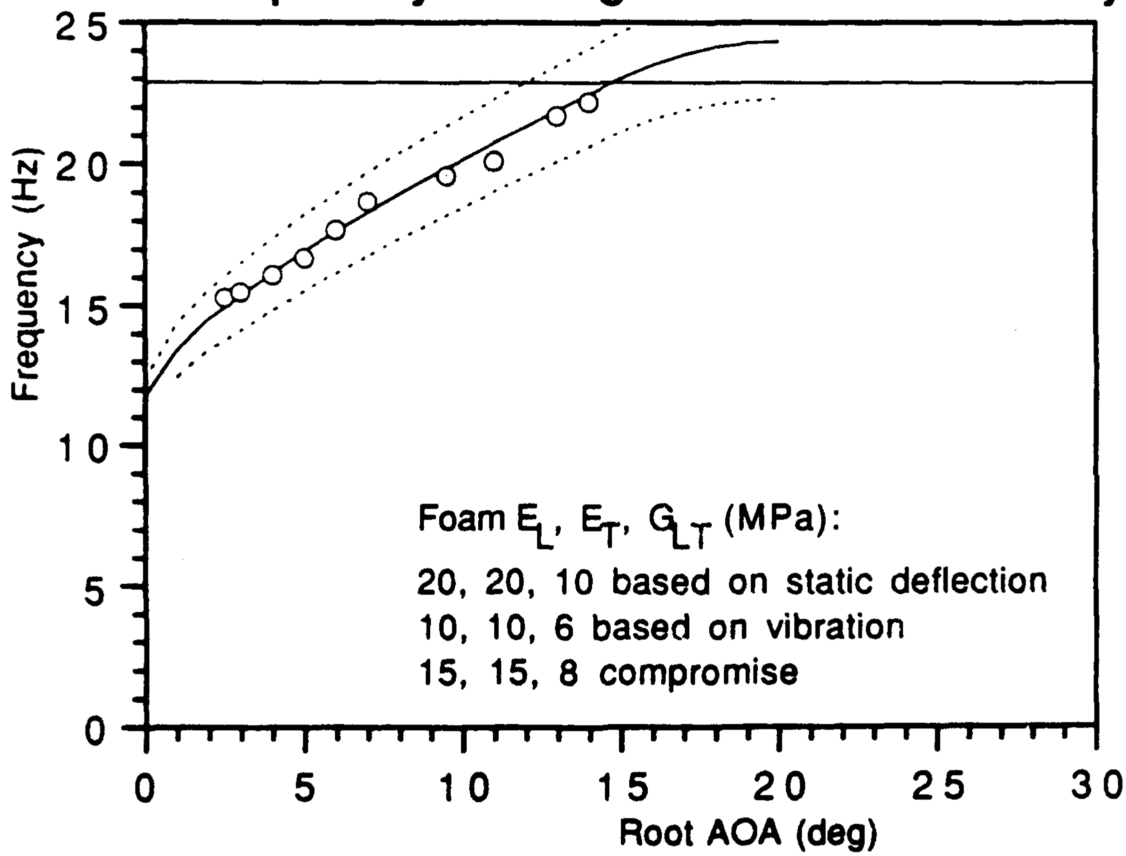
Tip angle, and deflection & angle oscillation amplitudes

24-JUL-91

$[0_3/90]_S$ Flutter boundary

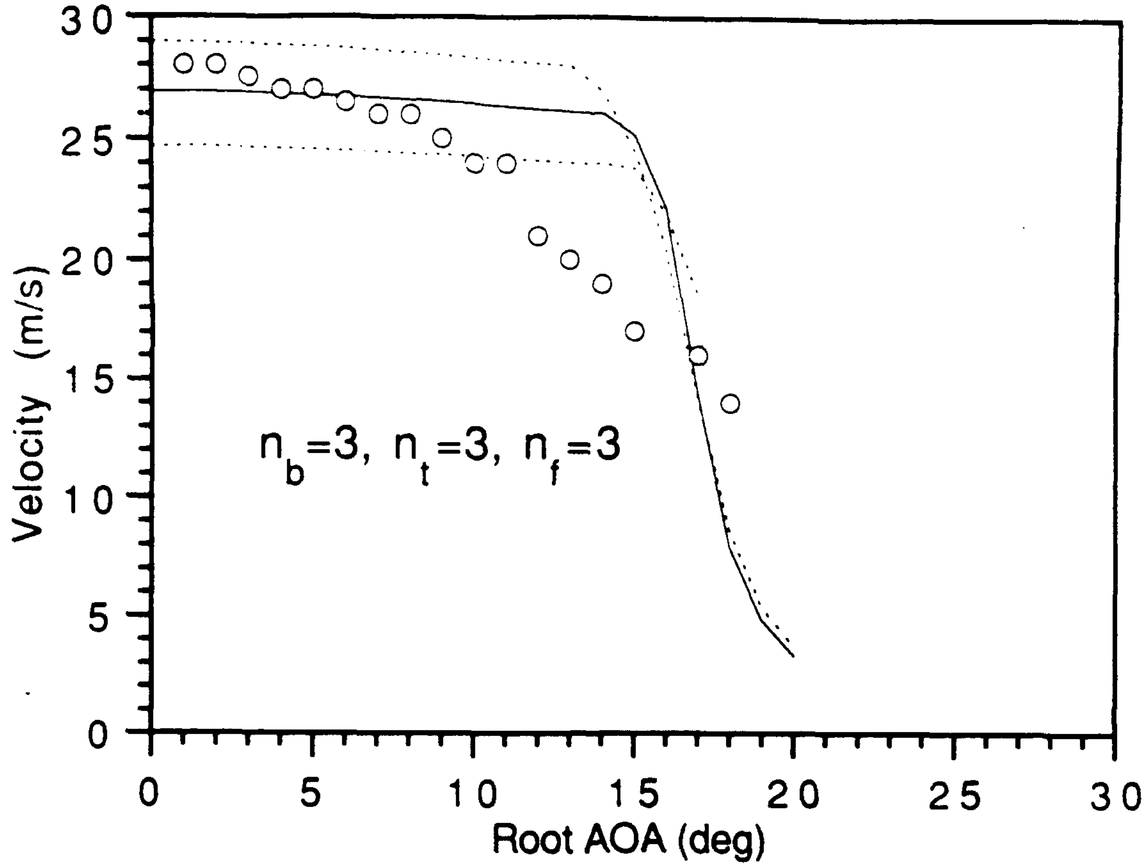


Frequency along flutter boundary

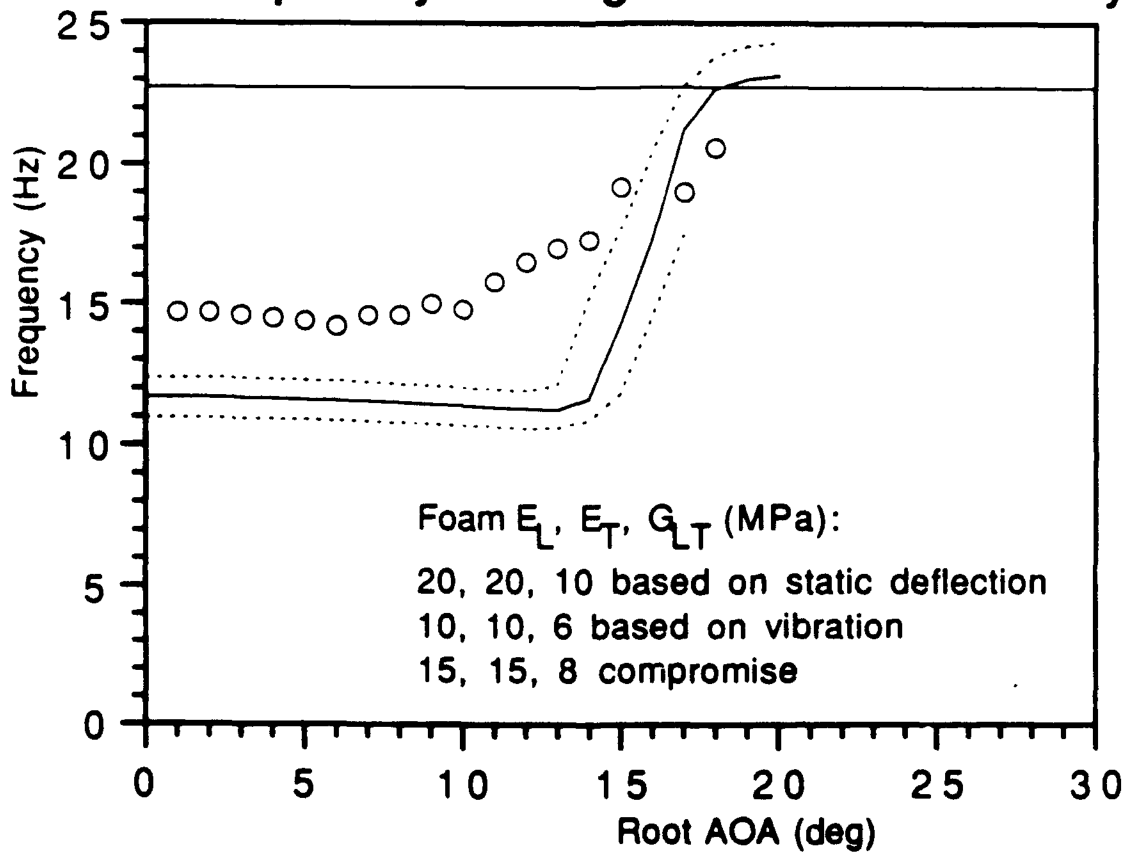


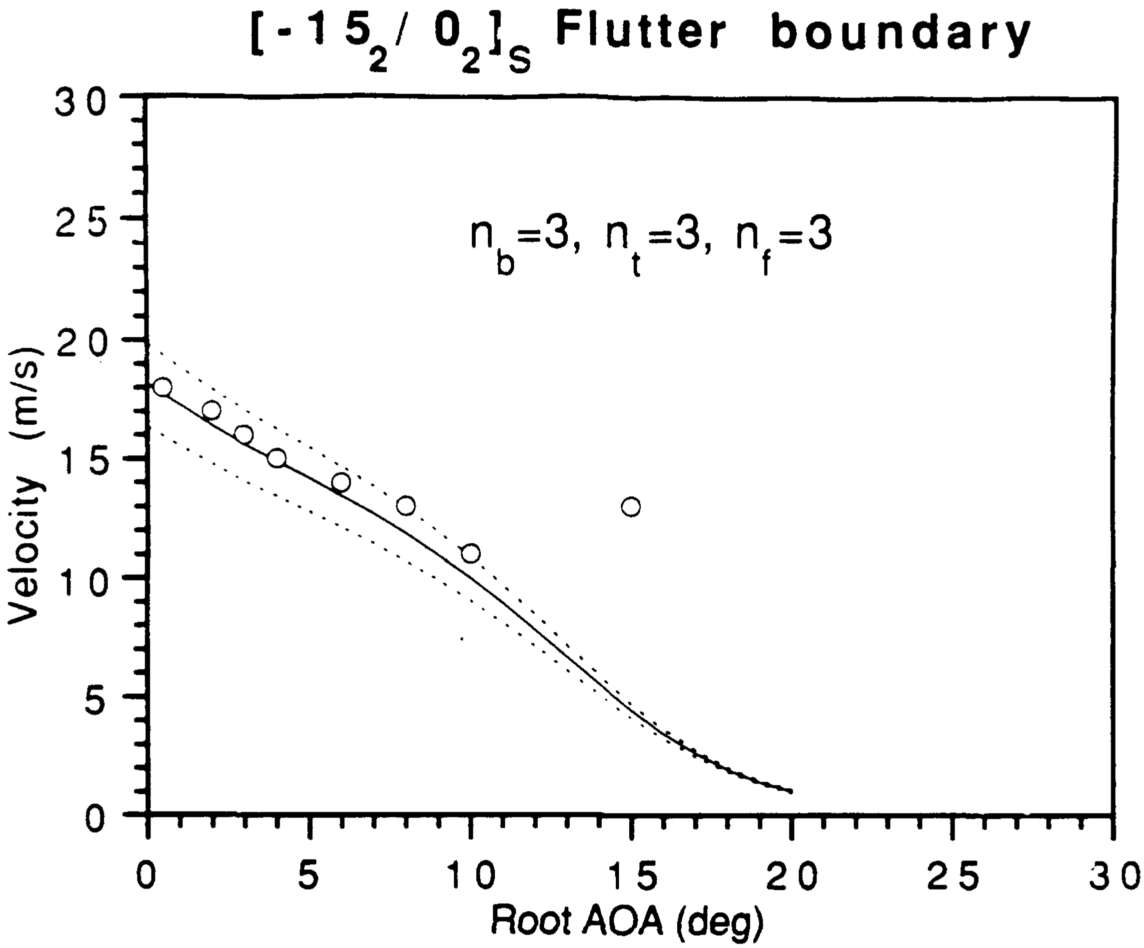
25-JUL-91

$[+15_2/\ 0_2]_S$ Flutter boundary

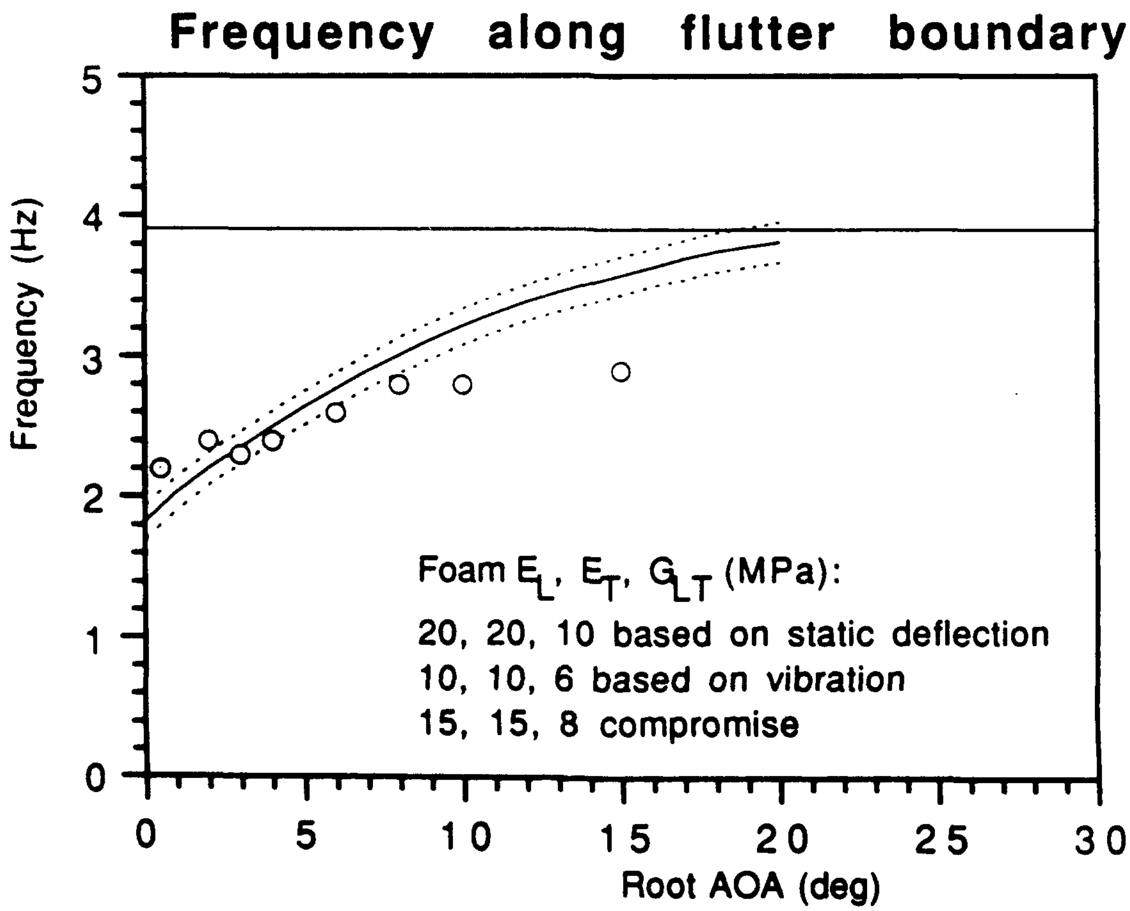


Frequency along flutter boundary





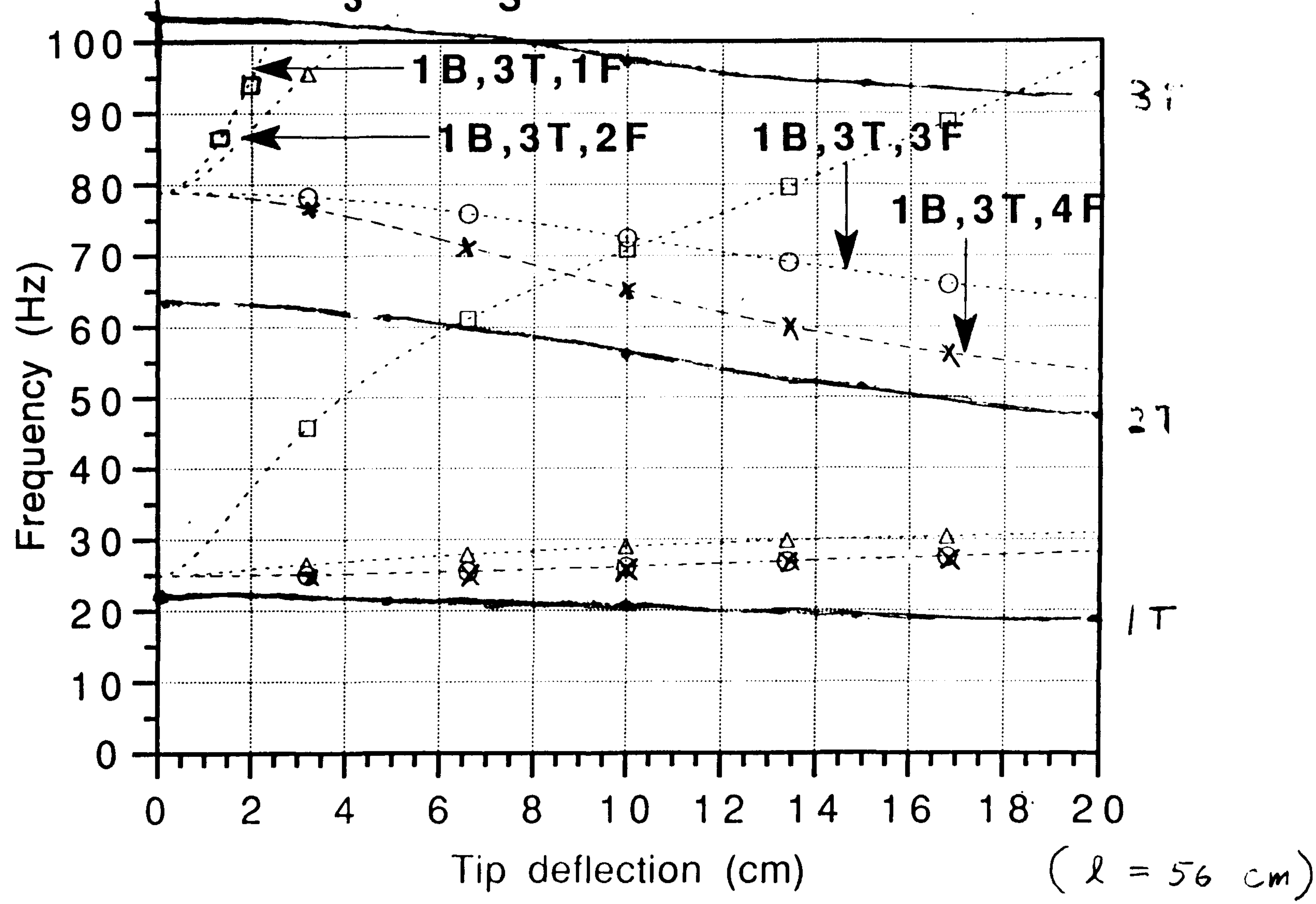
$[-15_2/0_2]_S$ Flutter boundary
n_b=3, n_t=3, n_f=3
Velocity (m/s)
Root AOA (deg)
0
5
10
15
20
25
30



Frequency along flutter boundary
Frequency (Hz)
Root AOA (deg)
Foam E_L, E_T, G_{LT} (MPa):
20, 20, 10 based on static deflection
10, 10, 6 based on vibration
15, 15, 8 compromise

24-JUL-91

$[0_3/90]_S$ wing, 22" span



CONCLUSIONS

- Developed analytic method to incorporate nonlinear structural and aerodynamic effects into a full, 3D aeroelastic problem

- Method used with simplified aerodynamics and lowest harmonic, but can be extended to more complex variations

- Experimental data obtained to check analysis

- Transition from linear, coupled-mode, bending-torsion flutter to single-mode, torsional stall flutter observed experimentally and predicted analytically

- Transition from linear divergence to bending stall flutter observed experimentally and predicted analytically